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DESIGN OF THE AIR FORCE RESEARCH LABORATORY MICRO AERIAL VEHICLE RESEARCH CONFIGURATION

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14. ABSTRACT

The Air Force Research Laboratory Munitions Directorate (AFRL/MN) is presently involved in many aspects of micro aerial vehicle (MAV) research. Among these are: advanced modeling and simulation models for MAVs, aero-structural interaction, advanced guidance techniques, hardware-in-the-loop simulations, and vehicle integration. In order to optimize collaboration within AFRL and also with outside research organizations, it was decided that a common MAV configuration be designed that would serve as a reference for current and future research. This paper describes a generic micro air vehicle that will serve as a "baseline" configuration. The MAV design incorporates a circular fuselage, a thin cambered wing, and a conventional tail. The MAV has a wingspan of 24 inches and a fuselage length of 17 inches. This paper will also detail the rational behind the design as well as provide initial aerodynamic properties and flight performance characteristics of the AFRL Generic MAV, herein called "GENMAV."

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Design of the Air Force Research Laboratory Micro Aerial Vehicle Research Configuration

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The Air Force Research Laboratory Munitions Directorate (AFRL/MN) is presently involved in many aspects of micro aerial vehicle (MAV) research. Among these are: advanced modeling and simulation models for MAVs, aero-structural interaction, advanced guidance techniques, hardware-in-the-loop simulations, and vehicle integration. In order to optimize collaboration within AFRL and also with outside research organizations, it was decided that a common MAV configuration be designed that would serve as a reference for current and future research. This paper describes a generic micro air vehicle that will serve as a "baseline" configuration. The MAV design incorporates a circular fuselage, a thin cambered wing, and a conventional tail. The MAV has a wingspan of 24 inches and a fuselage length of 17 inches. This paper will also detail the rational behind the design as well as provide initial aerodynamic properties and flight performance characteristics of the AFRL Generic MAV, herein called "GENMAV."

Nomenclature

ρ	=	air density
Γ	=	dihedral angle
ϕ, θ, ψ	=	Euler angles [roll, pitch, yaw]
b	=	wing span
c	=	chord
C_D	=	drag coefficient
C_L	=	lift coefficient
C_l	=	roll moment coefficient
$C_{l\alpha}$	=	roll moment versus angle-of-attack stability derivative
$C_{l\beta}$	=	roll moment versus sideslip angle stability derivative
C_{lp}	=	roll moment versus roll rate stability derivative
C_{lr}	=	roll moment versus yaw rate stability derivative
C_m	=	pitch moment coefficient
C_{mq}	=	pitch moment versus pitch rate stability derivative
$C_{m\alpha}$	=	pitch moment versus angle-of-attack stability derivative
C_{np}	=	yaw moment versus roll rate stability derivative
C_n	=	yaw moment coefficient
C_{nr}	=	yaw moment versus yaw rate stability derivative
$C_{n\beta}$	=	yaw moment versus sideslip angle stability derivative

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p, q, r = body rates [roll, pitch, yaw]
V = airspeed
x,y,z = coordinate axes in aircraft frame

I. Introduction

THE US Air Force Research Laboratory Munition Directorate (AFRL/MN)[1] is pursuing many avenues of research for micro aerial vehicles (MAV). Micro aerial vehicles (MAV) are characterized by small vehicle size ($\mathcal{O}$ 10 cm), low flight speeds ($\mathcal{O}$ 10 m/s), and low Reynolds number ($\mathcal{O}$ 10,000-100,000). The desire to develop MAVs is fueled by the need for increased situational awareness (especially in urban environments), remote sensing capability, "over the hill" reconnaissance, precision payload delivery, and aid in rescue missions. Figure 1 depicts where MAVs lay on the mass versus Reynolds number plot for flight vehicles and Figure 2 depicts some examples of MAVs. MAVs can be considered a sub-class of uninhabited air vehicles (UAVs). UAVs have been developed in recent years by leveraging traditional aerospace science technologies. However, the engineering maturity required for MAV development has not kept pace. For instance, due to the extremely small size of MAVs, the flowfield is dominated by separated flow regimes on the order of the vehicle size. Also, the small size of MAVs gives rise to small inertias which make the MAV more susceptible to wind gusts.

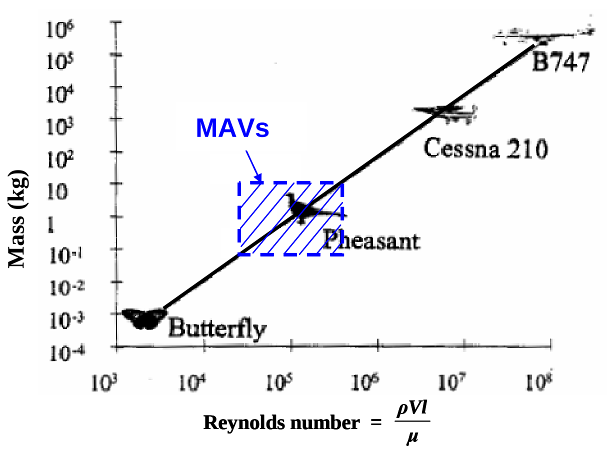


Figure 1. Mass versus Reynolds number for MAVs[2]

Figure 2. Examples of MAVs

In recent years, interest and development of micro aerial vehicles has been greatly increased. As such, many concepts and designs have emerged for MAVs. However, if one wants to study only certain aspects of MAVs, such as an advanced aerodynamic wing or advanced guidance, navigation, and control (GNC) methodologies, the various designs do not lend themselves well for trade studies. This need has led AFRL/MN to propose a "baseline" geometry for a MAV that can be openly distributed amongst various organizations for easy comparison of concepts and technologies. The aim of this paper is to describe in detail the geometry of the USAF Generic MAV, herein called "GENMAV," as well as providing initial aerodynamic prediction data as determined from a vortex-panel code.

II. The GENMAV Design

Design of the US Air Force Research Laboratory Generic Micro Air Vehicle, or "GENMAV," is loosely fashioned after similar MAV designs that have been studied in the past[3] and which are shown in Figure 3. Here are seen two micro air vehicles with 24" wingspans and 6" chords. These vehicles are designed for a flight speed between 10 and 50 mph which results in chord-Reynolds numbers from 50,000 – 250,000. This Reynolds number regime is characterized as "low" in the fixed-wing aircraft community where flow separation is of concern[4,5]. The designs depicted in Figure 3 also use a "V-tail" configuration and have a fuselage design that is not very well detailed in the literature. Additionally, details about the airfoil section were not very well defined.

It was decided that a standard, generic MAV configuration be defined that would serve as a reference for all future MAV studies. This MAV would be termed "GENMAV". GENMAV would be of similar size to the vehicles studied in Reference 3 but would employ simple conventional designs. Future MAV studies could begin with GENMAV as a starting point for design spirals and the resulting performance data would be referenced to a common design.

Figure 3. Previous MAV designs[3] studied that provided inspiration for a generic MAV design.

A. GENMAV Layout

GENMAV is a high-wing aircraft configuration with a circular fuselage and a conventional tail. GENMAV is depicted in Figure 4. Here it is seen that the vehicle is similar to a conventional aircraft design. Note that there is a "saddle" structure that is designed to smoothly transition the wing to the circular fuselage. Also note that the wings have a positive dihedral. While no engine or propeller is depicted in Figure 4, a tractor propeller is located at the front of the vehicle. However, no details about the propeller and engine will be defined at this point in the development.

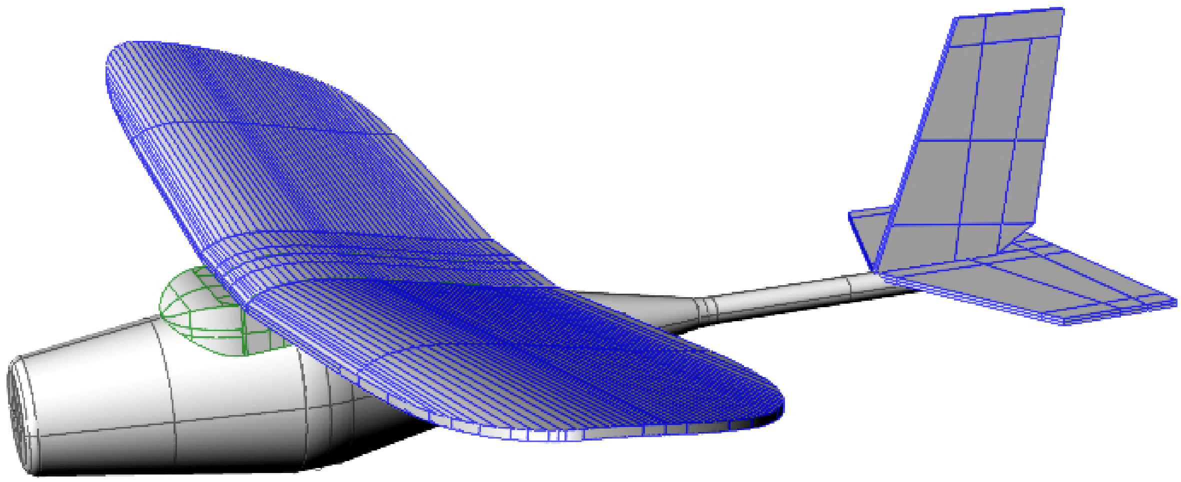


Figure 4. GENMAV configuration.

B. Fuselage

As mentioned, the GENMAV has a circular fuselage. The main reason for selecting a circular fuselage was for ease in aerodynamic analysis. However, the circular cross-section fuselage may be slightly more difficult to manufacture depending upon the construction method and it will be more difficult to place internal components. But it was felt that a circular design would provide a better baseline design. Figure 5 shows the side view of GENMAV where the fuselage shape is clearly seen. Note here the wing saddle which provides a transition between the wing and the fuselage. Additionally, this saddle allows for easy setting of the wing incidence angle which has been initially set to 5 degrees.

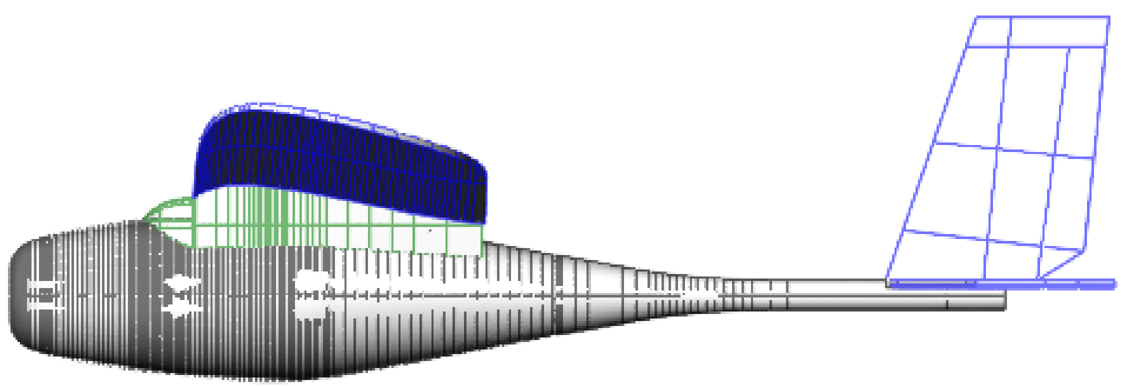


Figure 5. GENMAV side view showing fuselage design.

C. Wing

The GENMAV wing is a thin airfoil configuration with positive dihedral of 7 degrees. The root chord is 5” and the span is 24”. The GENMAV wing is less elliptical in planform than that of the MAVs in Reference 3. This was due to poor low speed performance attributed to tip-stall noted in flight testing of the MAVs of Reference 3. Because of this, a planform geometry was developed[6] in which the chord distribution is given by the expression

$$c(y) = C_r \sqrt{1 - \left(\frac{2|y|}{b}\right)^{\tau}}\ ,\ y = \left(-\frac{b}{2}, \frac{b}{2}\right). \tag{1}$$

Here, y is the spanwise coordinate, C_r the root chord, b the wing span, and τ = 8. This does not result in a rectangular wing, but rather a wing with a fairly constant chord for most of the span, with a rounded tip, as shown in Figure 6.

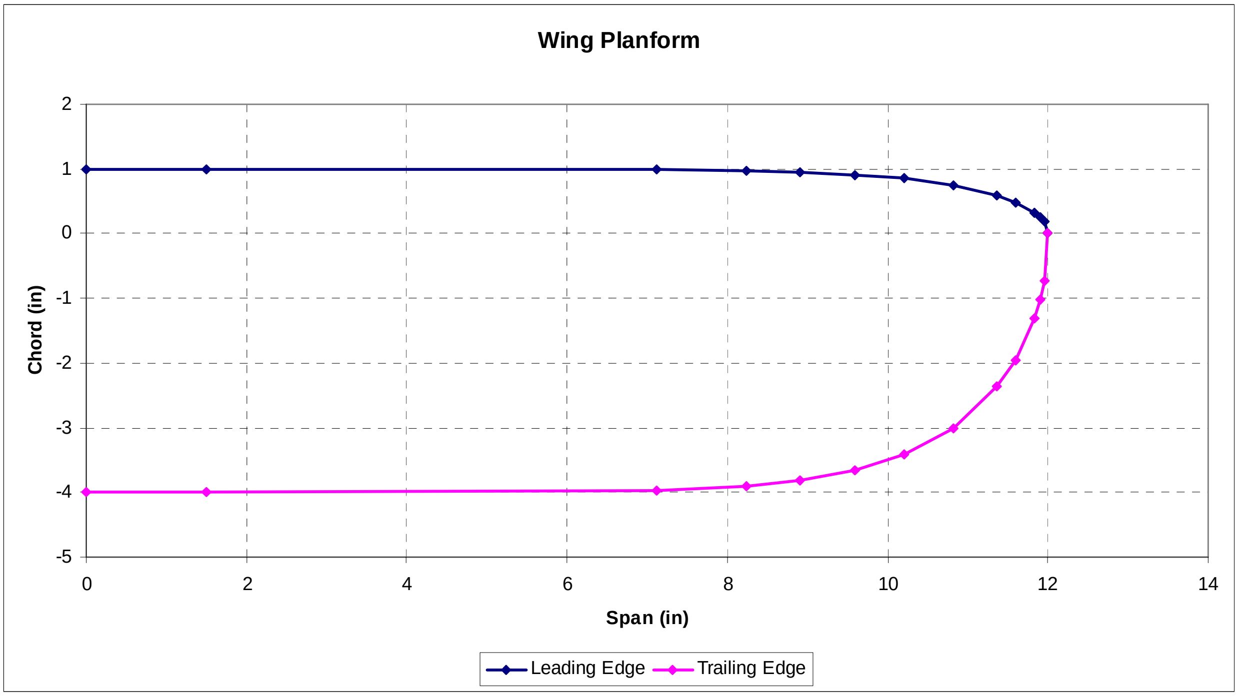


Figure 6. GENMAV wing planform.

The GENMAV airfoil shape is based upon a design from the University of Florida[7] as were the MAV designs of Reference 3. This airfoil did have some reflex incorporated into it as it was originally designed for a tail-less MAV concept. However, a rigorous redesign of the airfoil was not possible so it was decided to remove as much of the reflex beyond 30% of the chord length (x/c). The resultant airfoil is depicted in Figure 7 and the GENMAV airfoil coordinates are given in Table 1. Note that this airfoil shape is constant the entire span of the wing and that the curved tips are a simple cut-out from this constant chord.

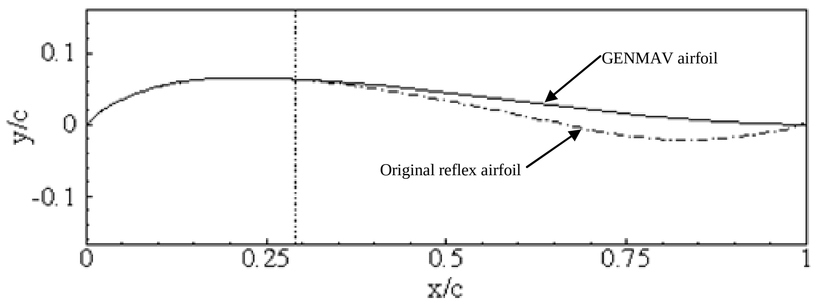


Figure 7. GENMAV airfoil section.

Table 1. GENMAV airfoil coordinates

x/c	y/c
0.00000	0.00000
0.01429	0.01256
0.02857	0.02241
0.04361	0.03120
0.06019	0.03928
0.07677	0.04586
0.09394	0.05132
0.11143	0.05566
0.12893	0.05895
0.14677	0.06140
0.16462	0.06308
0.18250	0.06412
0.20046	0.06465
0.21842	0.06474
0.23637	0.06448
0.25433	0.06394
0.27229	0.06318
0.29020	0.06225
0.30810	0.06117
0.32599	0.05998
0.34383	0.05869
0.36167	0.05733
0.37948	0.05590
0.39725	0.05440
0.41503	0.05285
0.43276	0.05124
0.45048	0.04958
0.46820	0.04785
0.48588	0.04607
0.50356	0.04423
0.52122	0.04233
0.53888	0.04037
0.55653	0.03836
0.57415	0.03630
0.59177	0.03421
0.60938	0.03208
0.62695	0.02993
0.64452	0.02777
0.66210	0.02562
0.67970	0.02348
0.69729	0.02137
0.71498	0.01931
0.73271	0.01731
0.75044	0.01539
0.76827	0.01356
0.78616	0.01185
0.80409	0.01026
0.82205	0.00881
0.84002	0.00751
0.85797	0.00635
0.87591	0.00533
0.89381	0.00444
0.91166	0.00365
0.92947	0.00292
0.94721	0.00222
0.96489	0.00149
0.98248	0.00065
1.00000	0.00000

D. Empennage

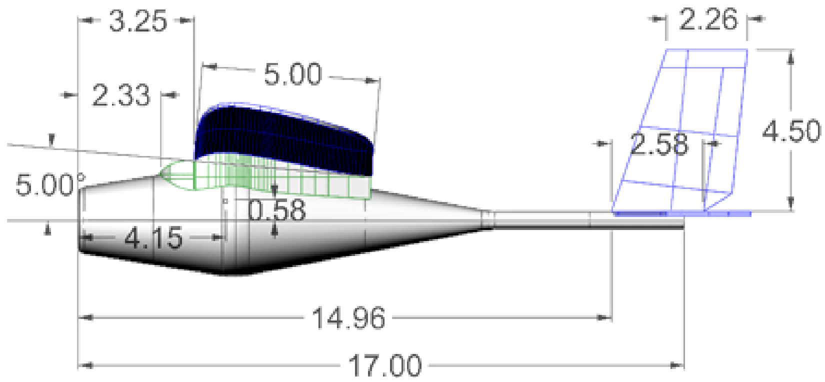
Conventional horizontal and vertical stabilizers were chosen for the GENMAV tail assembly. This was done to allow for a more conventional analysis of the GENMAV as well as alleviate any issues associated with a V-Tail. Many aeroprediction methods and simulations are based upon rudder and elevator commands so having a more conventional tail made the most sense. The rudder and elevator are approximately 25% of the tip chord for each stabilizer and run parallel with the trailing edge.

E. Engine

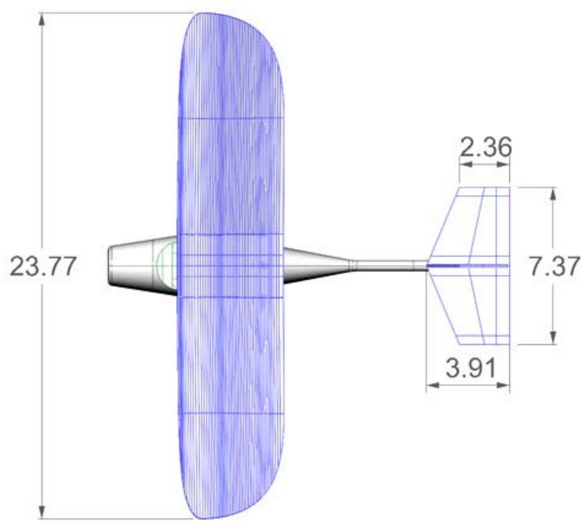
No engine or propeller is presently sized for GENMAV. It is anticipated that the engine will be aligned with the centerline of the fuselage and have an appropriately sized propeller disk.

F. GENMAV Dimensions

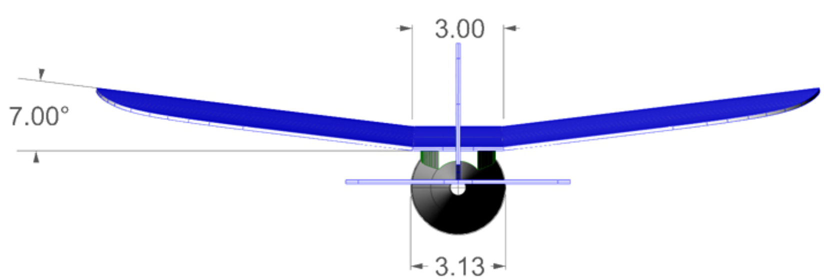
Figure 8 depicts the final GENMAV layout with dimensions. All dimensions are in inches. The center of gravity is located 4.15” behind the nose of the GENMAV and is vertically offset above the fuselage centerline by 0.58”. Note also that there is no wing dihedral for the first 1.5” of wing semi-span and then the dihedral is a constant 7 degrees. The vertical and horizontal stabilizers both start at 14.96” behind the nose of the GENMAV. The wing incidence angle is set to 5 degrees. The fuselage diameter is slightly larger than 3” at its widest point.



a) side view



b) top view



c) rear view

Figure 8. GENMAV dimensioned layout.

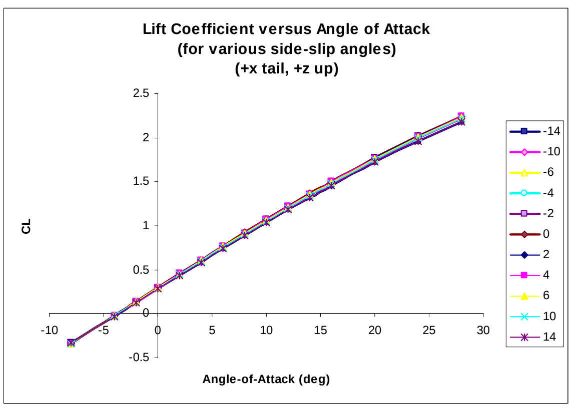
III. Aerodynamic Characteristics

An initial estimate of the aerodynamic characteristics of the GENMAV has been obtained through the Athena Vortex Lattice (AVL)[8] aeroprediction code, which is a vortex-lattice method. The flight regime of the vehicle ranges from about Mach 0.02 (15 mi/hr) to Mach 0.06 (45 mi/hr) at sea level conditions. Within this range, the aerodynamics do not change much and are mostly a function of angle-of-attack. AVL considers only the wing and tail surfaces to predict the vehicle aerodynamics. No contribution from the fuselage is considered. Hence, a drag correction must be added to the AVL results. A base drag correction of 0.06 was added to the drag data. This value was estimated from zero-yaw drag data given in Reference 3.

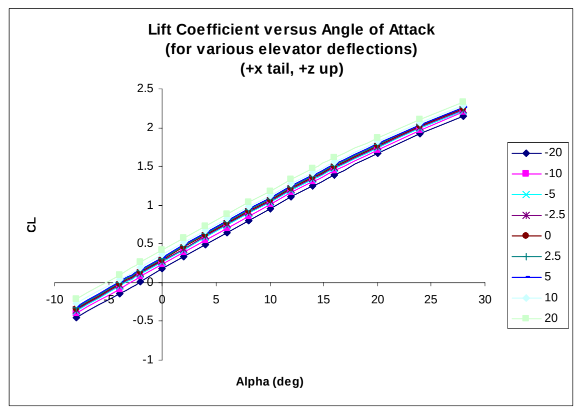
A. Lift and Drag data

Figure 9a shows the lift coefficient as a function of angle-of-attack for various side-slip angles and Figure 9b shows the lift coefficient vs. angle-of-attack for various elevator deflections. As AVL is a vortex-lattice code, flow separations are not predicted and therefore the lift data is fairly linear and does not show a stall angle. In the wind tunnel data of Reference 3, stall was seen at 8-10 degrees angle-of-attack.

Figure 10a depicts the drag data as predicted for GENMAV by AVL as a function of angle-of-attack versus side-slip angles and Figure 10b shows the same data for various elevator deflections. Note that the zero-yaw drag value of 0.06 is added to the drag data by AVL to account for the friction drag of the fuselage. Similarly, the lift-drag ratio versus angle of attack is given in Figure 11.

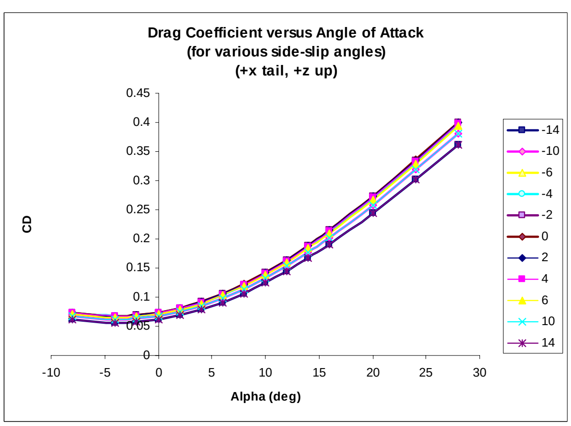


a) C_L vs. Angle-of-attack for various side-slip angles

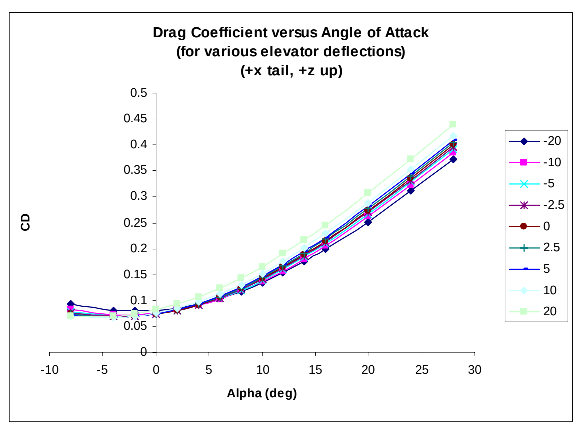


b) C_L vs. Angle-of-attack for various elevator deflections

Figure 9. GENMAV aerodynamic lift data.

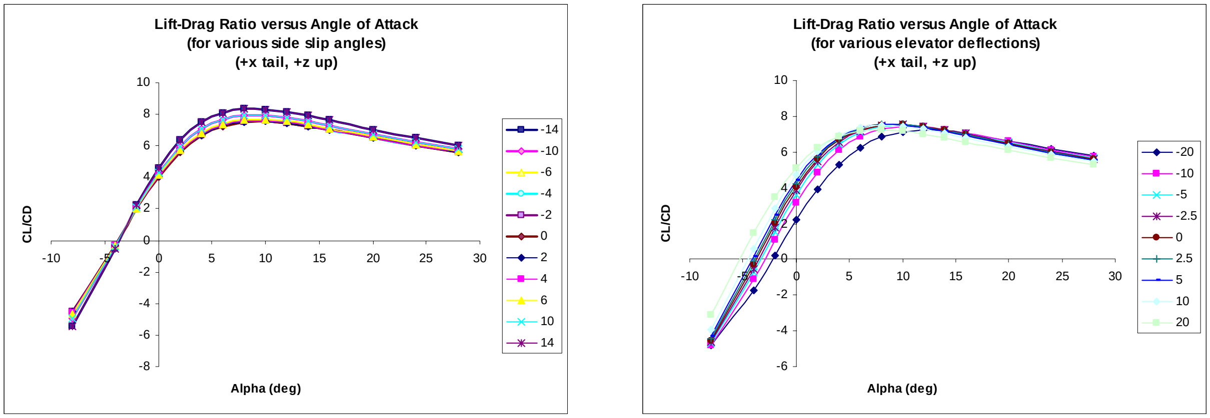


a) C_D vs. Angle-of-attack for various side-slip angles



b) C_D vs. Angle-of-attack for various elevator deflections

Figure 10. GENMAV aerodynamic drag data.



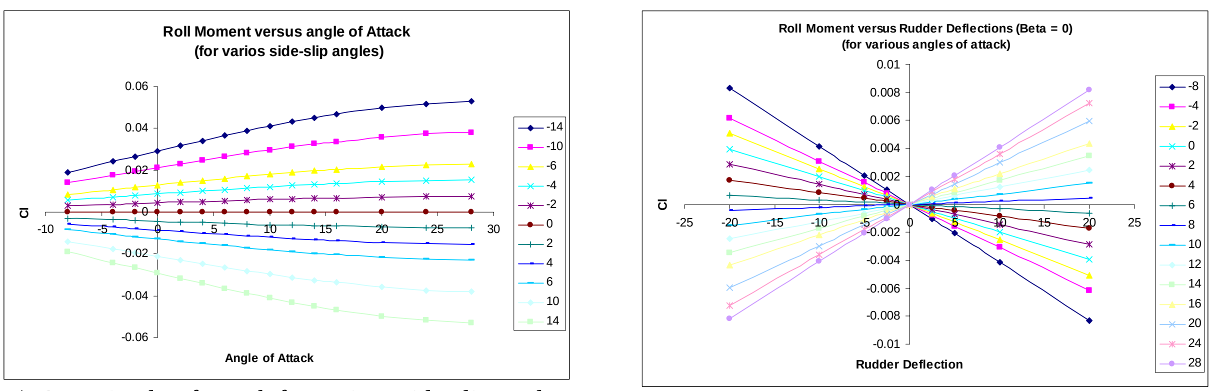
a) C_L / C_D vs. Angle-of-attack for various side-slip angles

b) C_L / C_D vs. Angle-of-attack for various elevator deflections

Figure 11. GENMAV lift-drag data versus angle-of-attack.

B. Moment Data

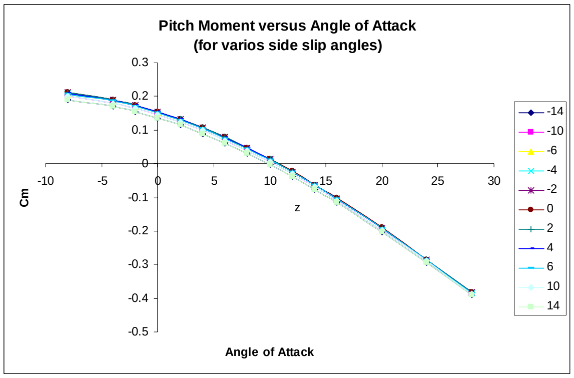
The aerodynamic moment data in roll, pitch, and yaw are also calculated by AVL. Figure 12 shows the roll moment coefficient as a function of angle of attack for various side-slip angles as well as the roll moment coefficient as a function of rudder deflection for various angles of attack. Figure 13 shows the pitch moment coefficient variation as a function of angle of attack for various side-slip angles as well as the change in pitch moment for various elevator deflections at various angles of attack. Finally, Figure 14 shows similar changes of the yaw moment coefficient with angle of attack and rudder deflections.



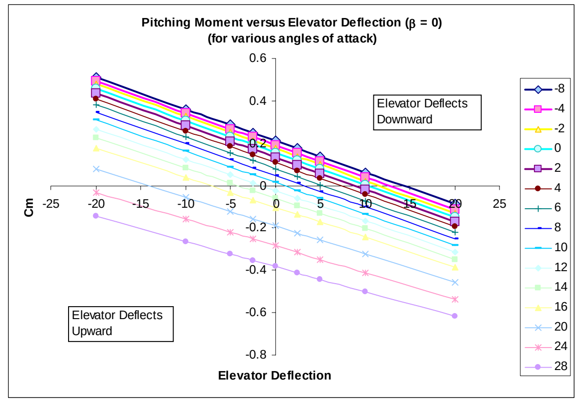
a) C_l vs. Angle-of-attack for various side-slip angles

b) C_l vs. Angle-of-attack for various rudder deflections

Figure 12. GENMAV roll moment data.

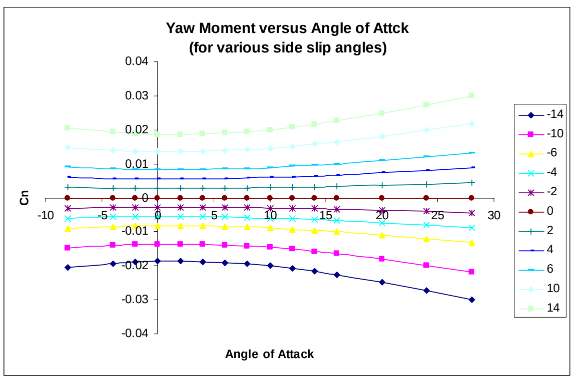


a) C_m vs. Angle-of-attack for various side-slip angles

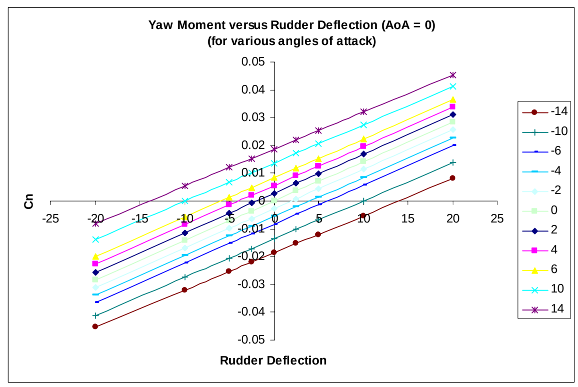


b) C_m vs. Angle-of-attack for various elevator deflections

Figure 13. GENMAV pitch moment data.



a) C_n vs. Angle-of-attack for various side-slip angles



b) C_n vs. Angle-of-attack for various rudder deflections

Figure 14. GENMAV yaw moment data.

C. Stability Derivatives

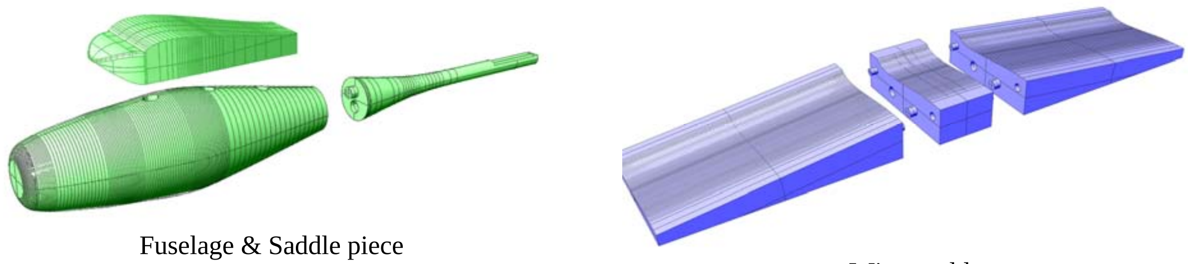
A summary of the stability derivatives as determined by AVL for the GENMAV configuration at a standard cruising speed of 30 mph is given in Table 2. Here it is seen that the airframe is stable in all three axes. Note also that the airframe exhibits very good spiral stability based on the relation ($C_{l\beta}C_{nr} / C_{n\beta}C_{lr}$) > 1 (in fact, $C_{l\beta}C_{nr} / C_{n\beta}C_{lr}$ equals 12.0).

Table 2. GENMAV Stability derivatives

$C_{l\beta}$	C_{lp}	C_{lr}	$C_{m\alpha}$	C_{mq}	$C_{n\beta}$	C_{np}	C_{nr}
-0.162	-0.496	0.191	-1.45	-12.5	0.005	-0.040	-0.071

IV. Prototyping

A first prototype of the GENMAV was recently completed. This was accomplished at the AFRL/MN Micro Munitions Fabrication Laboratory. A 3-D printer was used to "print" the fuselage and wing molds. Figure 15 depicts the fuselage sections and saddle piece as well as the wing mold that were used for prototyping. With the completed fuselage mold, carbon-fiber cloth is used to wrap the mold. For the wing, a carbon-fiber cloth is used in the wing mold and is vacuum-sealed during the curing process. The finished wing conforms to the shape of the mold. The final planform of the wing is cut after the wing is dry. Flat carbon-fiber panels are used for the empennage section.



Fuselage & Saddle piece

Wing mold

Figure 15. GENMAV Component CAD files for 3D printing.

Figure 16 shows the completed GENMAV prototype which was recently installed in the Oregon State University low speed wind tunnel. Unfortunately, data analysis was not possible before the publication of this paper.

Figure 16. Prototype GENMAV in Oregon State University Wind Tunnel.

V. Conclusions and Future work

This paper outlines the geometric properties of the AFRL Baseline Generic MAV (GENMAV) configuration. Aerodynamic analysis was performed on this configuration with the Athena Vortex Lattice (AVL) aeroprediction code. The AVL code gave reasonable approximations to the GENMAV aerodynamics. GENMAV provides the aerospace community a common starting ground: a conventional, stable airframe from which different MAV technologies and trade studies can be applied. It is hoped this basic framework will aid the research community by allowing a true comparison to be made between modifications applied by various organizations.

Future work will include more aerodynamic analysis through wind tunnel testing (presently underway) as well as computationally. The prototype GENMAV will also undergo flight tests as well in which flight data will be recorded and analyzed. These tests include defining the maximum / minimum airspeed and observing the vehicle's handling qualities in roll, pitch, and yaw. Once familiarization with the air vehicle is complete, further flight testing can take place to document the flying qualities of the baseline MAV configuration. Data from these flight tests will act as the control point to which modified versions of the MAV can be compared. Flight test data can also be used to validate a 6-degree-of-freedom (6-DOF) simulation currently under development. It is hoped other organizations will adopt the GENMAV configuration and perform analysis on it as well to further increase the understanding of the configuration.

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